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Infrastructure Cost Issues Related to Inductively Coupled Power Transfer for Electric Vehicles

Jasprit S Gill^a, Parth Bhavsar^{b*}, Mashrur Chowdhury^b, Jennifer Johnson^c,
Joachim Taiber^a, Ryan Fries^d

^a*CUICAR, 4 Research Drive, Greenville, South Carolina – 29607, USA*^b*Clemson University, Glenn Department of Civil Engineering, 216 Lowry Hall, Clemson, South Carolina 29634, USA*^c*Kimley-Horn & Associates, Inc., 2 Sun Court, Suite 450, Norcross, Georgia 30092, USA*^d*Southern Illinois University Edwardsville, Department of Civil Engineering, Box 1800, Edwardsville, IL 62026, USA*

Abstract

The electrification of vehicles has been accelerated over the last few years due to tighter emission regulations, volatile fuel prices, and progress in standardization as well as improvement of battery technologies. Key hurdles of electric vehicles (EV) to gain a larger share in the automotive market are the cost of the energy storage system (ESS) and the density of the EV charging infrastructure. The achievable range of an EV or full electric driving of a plugin hybrid electric vehicle (PHEV) is limited by its battery capacity. The time to recharge the battery is related to the power level of charging as well as allowable charging parameters to protect the battery life. In order to overcome the constraints of limited range of EVs (all electric driving) as well as the cost of ESS, inductively coupled power transfer (ICPT) is an interesting technology path to be considered, in particular if applied as opportunity (stop-and-go) or in-motion charging (also called dynamic wireless charging or move and charge). In-motion wireless charging could lead to significant reductions of the vehicle-related cost of electrification but this comes with the price of an infrastructure that needs to be built and maintained. In order to design the ICPT infrastructure and calculate the cost of construction and operation, certain assumptions have to be made with respect to the vehicle specifications, the specification of the charging system itself and the cost of integration into the existing road infrastructure. The objective of this paper is to provide a thorough analysis of the cost associated with the implementation of a dynamic ICPT infrastructure to support the operation of electrified vehicles and to present transportation agencies a business model that can provide a starting point for the development of a new EV infrastructure.

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* Corresponding author. Tel.: +1-864-384-0247; fax: +1-864-656-0145.

E-mail address: parthb@clemson.edu

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1. Introduction

Although the source of electricity, whether renewable or non-renewable, influence the total sustainability measure of electric vehicles (EVs), these vehicles significantly contribute to a sustainable transportation community as they reduce pollutants to the environment. Despite a number of current drawbacks with these zero-emission vehicles, EVs are expected to significantly penetrate the market by year 2020¹. One of the greatest factors restraining the market penetration of EVs is the linear relationship of EV driving range and battery size, or cost. Because the battery pack is known to account for a significant percentage of the total vehicle cost, it is often restricted in size, thus limiting the EV's total driving range. Although a larger battery may result in a longer driving range, it also significantly increases the cost and weight of the EV². When dealing with EV-design, many engineers focus significantly on the design of the battery in efforts of reducing costs. There are numerous variables, which are taken into consideration in the design phase of EV batteries such as size, life, cost, and safety³. In addition, a major technical issue that requires attention throughout the world is the design, construction, maintenance, and operation of the charging station (CS) infrastructure, which EVs are so dependent upon. Ultimately, the goal of such infrastructure is to provide the EV with unlimited driving range while still optimizing battery size and vehicle costs. CS infrastructure will be supported more and more as EV market penetration increases, supporting the design of more innovative charging schemes that will propel EV technology into the future.

Charging the battery for an EV must be safe, affordable, fast, and convenient. The travel distance of EVs is heavily dependent upon the battery cycle and the location of the CS. Although numerous CSs have been built in recent years, the success of EVs will be decided by the ease of charging⁴. Numerous studies have been completed that compare both the cost and time efficiency of varying charging schemes including: home, regenerative braking, solar, park-and-charge (PAC), battery swapping, and move-and-charge (MAC). Home charging is convenient because it is typically done during the evening hours with a light, onboard charger (Level 1), which comes as a standard accessory with an EV and takes about 8-16 hours for a full charge depending upon the type of EV⁵. Level 2 chargers cost about \$1000 to \$2000 with installation and can charge a car like Nissan Leaf in about 4 hours^{6,7}. Regenerative charging and solar charging are typically only used as charging enhancers to extend the driving range and not to charge the battery as the sole source of power. The PAC method is typically done at CSs using either Level 2 or Level 3 chargers. Level 3 PAC system, or fast-charging station, can provide a 100-mile range charge in as little as 15 minutes⁸. Currently, these CSs cost upwards of \$15000 to install⁹. Another alternative to addressing an EV's limited range is a process known as "battery swapping" where EV drivers can swap out their depleted battery for a freshly charged battery without having to wait through the charging process¹⁰. This process, however, is hindered by the fact that EV batteries are not standardized for varying vehicle models¹¹. A more recent charging scheme, MAC, provides the drivers with the convenience of charging their vehicles while driving by using dynamic inductively coupled power transfer (ICPT). The EV is essentially driving through the charging zone because the MAC system is actually constructed into the road itself⁸.

Recently, there have been many studies undertaken with the purpose of developing smart and efficient charging models. By using these technologies, motorists can charge their vehicles on-the-go, thereby eliminating the shortcomings of range and waiting times at CSs. Lukic et. al.¹² studied the use of a dynamic ICPT option, concluding that if the ICPT track has sufficient coverage, motorists could theoretically drive indefinitely, without waiting to charge their vehicles. Gil et. al.¹³, on the other hand, identified the technology and infrastructure challenges for the transition to dynamic ICPT.

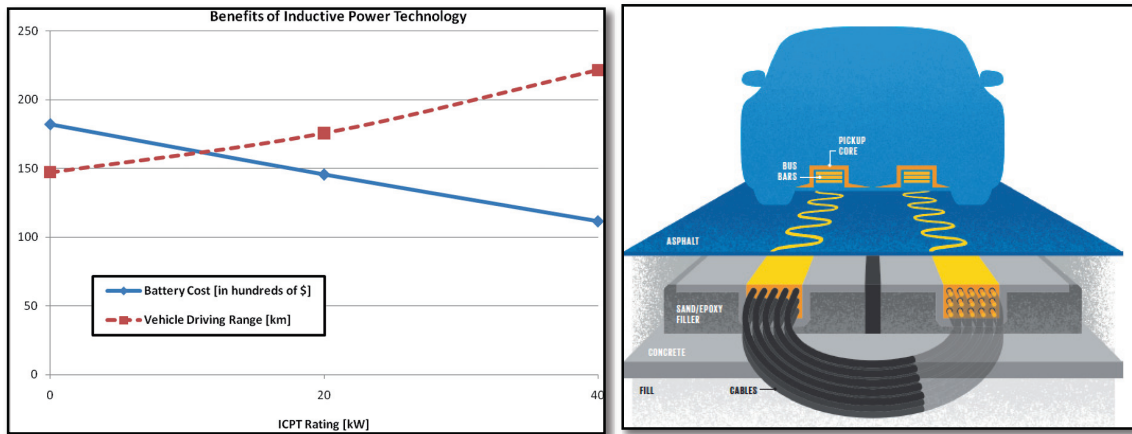


Fig.1. (a) Benefits of ICPT in EV Charging Operations²; (b) Dynamic ICPT System for EVs¹⁷

Other research is being conducted to evaluate the benefits of wireless charging technologies. In a study by Karalis et. al.¹⁴, the use of electromagnetic coupling was considered as a tool for energy transfer over mid-ranges. In another study, the experimental setup of wireless power transfer using helical antennas was studied. By using magnetic coupling for the energy transfer, they studied the effect of distance between the transmitting and the receiving antenna on the efficiency of energy transfer¹⁵. Lorico et. al.² demonstrated the use of ICPT to decrease average battery costs while maintaining EV range as well as to increase average EV range while maintaining a battery pack size of 28kWh for the average of three drive cycles, including federal urban driving schedule (FUDS), federal highway driving schedule (FHDS), and Clemson University International Center for Automotive Research (CU-ICAR) neighborhood drive cycle. The battery pack costs savings were found to be approximately 20% and 39%, and the vehicle driving range was found to increase by approximately 20% and 50% for the 20kW and 40kW ICPT rating cases, respectively. This study also determined that in urban settings with an urban dynamometer driving schedule (UDDS) driving cycle, only 1% of the driving cycle had to be covered by ICPT tracks in order for the EV to acquire an unlimited driving range. As shown in Fig. 1(a)², the zero ICPT rating represented the base case scenario where ICPT was not used for EV charging.

The Inductively coupled power transfer is a form of wireless power transfer technology that can alleviate electric vehicle user's "range anxiety" while also minimizing EV battery costs. In the dynamic ICPT, power sources are placed in the road and electric vehicles receive the power wirelessly while moving on these sources at the average speed of roadway traffic. When charging an EV, it is important to ensure that its energy requirements can be sufficiently met by the power capabilities of the CS infrastructure, but advanced infrastructure for charging schemes like dynamic ICPT requires significant capital and operating costs. Several infrastructure cost issues related to the construction, maintenance, and operation of such facilities need to be addressed. In addition, there must be a clear understanding on how such innovative infrastructure will effect coordination between the numerous public and private stakeholders involved, including departments of transport (DOTs) and electric utility companies. The objective of this paper is to analyze the costs associated with a dynamic ICPT infrastructure and to present a business model that these agencies can use for identifying and addressing the potential issues to cost-effective dynamic ICPT for EVs.

2. Overview Of Inductively Coupled Power Transfer

Traditionally, EVs are recharged at stationary sources, which results in a significant amount of time loss at CS. A more innovative charging scheme now being considered is known as dynamic inductively coupled power transfer (ICPT). As against a stationary ICPT system, which charges an EV without any physical connection in between the CS and the EV, dynamic ICPT is able to charge an EV wirelessly as it drives over a powered track¹⁶. In such

systems, transmitting cables, or tracks, are embedded in the road and pickups (power receiving coils) are installed in the underside of an EV, as shown in Fig. 1(b)¹⁷. In September 2010 and May 2012¹⁸, Bombardier Transportation demonstrated dynamic ICPT by installing a contactless and catenary free PRIMOVE system for trams in Augsburg, Germany. Shin et. al.¹⁹ developed a 100KW dynamic ICPT system with 80% efficiency for up to 26cm air gap. In August 2013, the system was installed in two buses, called on-line electric vehicles (OLEV), which began public service in the city of Gumi, South Korea²⁰.

The greatest benefit of a dynamic ICPT system is that it eliminates the energy storage shortcomings of EVs by allowing them to charge while driving without the additional waiting time. The ultimate goal is to extend the EV driving range to distances of over 500 kms while also significantly decreasing the size and cost of the EV battery. As EV battery size continues to decrease, the cost will begin to shift from the electric vehicle to the complex infrastructure needed to charge such vehicles while in-motion. Public agencies, like state DOTs and electric utility companies, will have to invest significant costs constructing, maintaining, and operating EV charging infrastructure.

3. Dynamic ICPT Infrastructure Cost Issues

This section presents costs for each element in the dynamic ICPT system so that the stakeholders involved can be aware and prepared to handle all of the cost issues. According to the Electric Power Research Institute (EPRI)²¹, an ICPT system, or what they refer to as an integrated energy storage system, consists of three major components: energy storage system (ESS), power conversion system (PCS), and balance of plant (BOP). This section of the paper will give an in-depth literature review of the major costs incurred due to installing ICPT infrastructure for EVs, including capital, maintenance, and operational. As agencies begin investing in such infrastructure, they must be cautious in estimating the costs of ICPT infrastructure as history has proven that the costs associated with PCS and ESS systems are heavily under-estimated²¹. In addition, it must also be taken into consideration that transferring large amounts of energy requires suitable batteries, which can also be very costly.

3.1 Capital Cost Issues Associated with Dynamic ICPT Infrastructure Construction

The current estimate of the construction and commissioning of ICPT infrastructure is at \$235,790 /lane km, for power requirement of 400KW/km in one direction¹⁹. However, the cost of the grid converter(s) would have to be taken into account depending on the power level of the system. In determining the cost of these large utility power converters, the EPRI²¹ report was used to estimate the cost of grid-level power conversion system (PCS) installations. The PCS includes all components necessary to deliver the electrical energy from the power strips to the ESS on the EV as well as to discharge stored energy to the utility grid. For dynamic ICPT charging, it was determined that this would be Type III PCS for prompt discontinuous operation, which is a short duration power quality (SPQ) application. Although the converter must remain utility connected and powered up in order to energize the roadbed transmit coils when needed, the Type III PCS will have very low standby losses as it is not required to be constantly energized. In other words, the PCS would remain idle until an EV passed over the transmit coils. The PCS can also be used to provide grid reactive power support during its idle time. The total cost of the PCS was estimated using Equation (1), obtained from EPRI²¹ report, which was developed from historical data of PCS vendors, and for this case, a pulse factor (P_f) of 3.5, which was the middle value of the typical 2 to 5 pulse factor range, was assumed. Therefore, the total cost of the PCS would amount to 185 \$/kW. So, a 400KW grid converter for ICPT would be approximately \$70,000 fully installed, without including the additional costs associated with the grid point of common connection (PCC) transformer²¹.

$$\text{Type III PCS COST} = 365 * P_f^{-0.54} \quad (1)$$

3.2 Cost Issues Associated with Dynamic ICPT Infrastructure Maintenance

Typically, public agencies, like the DOT, are not only responsible for road construction (highway development programs) but also for road maintenance (rehabilitation programs). With ICPT infrastructure being introduced into the scenario, however, there are a number of added costs associated with the maintenance of the highway infrastructure. The initial problem in dealing with the ICPT infrastructure is that the DOT's pavement management

schedules and costs will significantly change. Significant levels of coordination will be required between the DOT's pavement management schedules and the electric utility's power strip management schedules. It will take significant amounts of costs to train employees in managing the complex ICPT system as well as additional time and costs in efficiently merging both management database systems used to monitor the pavement and the ICPT infrastructure.

ICPT infrastructure in the pavement itself consists of the transmission coils in the roadbed, which is used to provide power to the passing EVs. Although these transmission coils can be installed in both asphalt and concrete pavements, most previous work has investigated application in concrete pavement. These works have found that transmission coils should be installed directly above any re-bar to minimize parasitic losses from the inductance of adjacent metals. As a result, losses appear to the grid converter as a continuous loss during energized periods which is directly comparable to the line losses on transmission and distribution lines that utilities currently face, which is simply a cost of doing business²¹. Other studies have found that these roadway embedded coils, or continuous system cables, should be suitable for the lifecycle of the concrete roadbed. Typically, the coils are installed as long sections of pre-stressed and reinforced concrete modules having transmit coils and attachment cables and then are typically overlaid with synthetic concrete or some plasticizer, much like the interconnected pre-stressed sections of guide way used in China's construction of the Shanghai MAGLEV train²². These sections, while not protected by the roadbed reinforcement rods, are not installed in the lane wheel ruts left by large over-the-road trucks, and thus, may not require significant amounts of maintenance or replacement. Therefore, while it may appear that typical maintenance costs will remain low for the dynamic ICPT infrastructure itself, costs may begin to accumulate for DOTs in training existing staff and in hiring more personnel to monitor the pavement infrastructure for potentially harmful conditions such as debris. Furthermore, ICPT systems are complex and require advanced expertise acquired only through intensive training; therefore, the stakeholders must implement training programs to educate their personnel, something that will be very time consuming and expensive. Other operational issues which may increase maintenance costs will include resilience to freeze-thaw cycles in colder regions, additional equipment to heat ICPT components in winter and cool them in summer in order to protect the system from adverse weather conditions.

3.3 Cost Issues Associated with Dynamic ICPT Infrastructure Operations

When dealing with the operational costs of the dynamic ICPT infrastructure, both DOT and utility companies will have numerous cost issues to consider. A stable grid will have balanced power generation throughout normal and abnormal conditions; a reliable grid will be able to handle unexpected demands without failing and be able to quickly recover if failure does occur for some unforeseen reason²³. The utility companies' major costs will arise in distribution system expansion costs in order to ensure stability and reliability within the electric grid. The estimated full cost of upgrades to the grid network in order to bring the generation on line is approximately \$700/kW for transmission and distribution (T&D) costs and \$70/kW-yr in peak generation costs²⁴. In order to anticipate the scale of such costs, utilities must perform what is known as power system planning. The objective of such efforts is to strategically plan for the long-range expansion of the generation, transmission, and distribution systems in order to meet the added energy demand that EVs place on the utility grid. The goal is to supply adequate amount of ICPT infrastructure capable of meeting the predicted future load forecast while also minimizing infrastructure expansion. The utility companies must account for both economic factors and load requirements in calculating distribution system expansion costs²⁵. The major issue that arises here is that the future electrical load is very difficult to predict as many variables will determine how quickly and to what extent EVs will penetrate the transport sector.

Smart-charging management is one strategy that the utility companies may consider while trying to ensure that the electric grid is able to meet EV energy demands. This can reduce peak demand through processes such as time-of-use rates and load control²⁴. Time-of-use rates is a type of demand response control in which EVs are charged a higher \$/kW rate during peak hours in order to control the load and to avoid severe situations like the North-eastern United States blackout in 2003²⁶, which resulted in billion dollar losses. In addition, electric utilities can use load scheduling, a process allowing utility companies to balance energy supply and demand in real-time. This method can also allow utilities to reduce energy costs by using more renewable energy sources as load scheduling matches charging demand to irregular renewable generation supply, such as wind and solar energy²⁴. The utility companies can also encourage vehicle-to-grid (V2G) enabled EV owners to participate in the grid ancillary services by applying a charge scheduling model to lower the investment in both operational and maintenance cost²⁷. Pricing schemes like these will help utility companies reduce their new generation, transmission, and distribution costs.

4. Business Model To Fund ICPT Infrastructure Costs

With increasing fuel economy of passenger vehicles, the public sector has already experienced significant shortfalls in funding transport infrastructure, for example the U.S. federal gas tax¹¹. Integration of EVs into the transport sector, will only increase this lack of funding¹¹. Hence, the development and integration of a dynamic ICPT infrastructure requires a new and radically different business model for public agencies and private investors. This section discusses a new business model to successfully fund the dynamic ICPT infrastructure. Fig. 2 is a conceptual flow chart of this business model. The model leads to the development of a joint company, with public transport agencies like DOT, utility companies and interested private investors as participants. This joint company should be utilized throughout the entire lifespan of the ICPT infrastructure to facilitate the raising of funds needed to maintain and operate it throughout the years to come.

In this business model, these participants must be prepared to fund the significantly large initial construction costs of the dynamic ICPT infrastructure. The public agency would enter into a joint contract with the utility company and with other interested private investors in what is known as public-private partnership (PPP). In addition to supporting the initial costs of the ICPT infrastructure, the public agency (DOT in fig. 2) would maintain set standards for the highway infrastructure (similar to the national intelligent transportation system, ITS, architecture), while the EV service providers (utility company or private investors), would be responsible for providing the electrical energy for charging and for ensuring that the ICPT tracks themselves are properly maintained. The service providers would recover this cost by collecting the charging fee (with road usage fee as a part of it) from the EV drivers and road usage fee from Non-EV drivers using the infrastructure²⁸.

The public agencies can leverage PPPs as a powerful financial tool capable of raising significant amounts of revenue for the transport needs of public. Historically, public agencies have not done a good job of utilizing PPPs. As reported by the Texas DOT in 2007, only \$8 billion of the \$700 billion available revenues were actually utilized in public transport projects²⁹. These PPPs will ease the burden of identifying funds to build and maintain the dynamic ICPT infrastructure from DOT and accelerate the implementation. The private investors may develop a contract-based relationship such as Build-Operate-Transfer (BOT) or Build-Own-Operate-Transfer (BOOT). The major benefit of this business strategy for the DOT is that they are able to maintain their centralized role in managing the transport network, much like the way ITS infrastructure is currently installed, while still receiving significant amounts of aid in funding the system.

In this business strategy, both the non-EV and EV drivers would pay to use the highway infrastructure and ICPT infrastructure respectively. The non-EV drivers would be charged based on a road-usage fee, or a pay-per-mile contract, with the public transport agency. In case of PPPs, private investors operating and maintaining the section of the roadway may charge an additional fee to non-EV drivers. These road-use charges (RUCs) would be based on

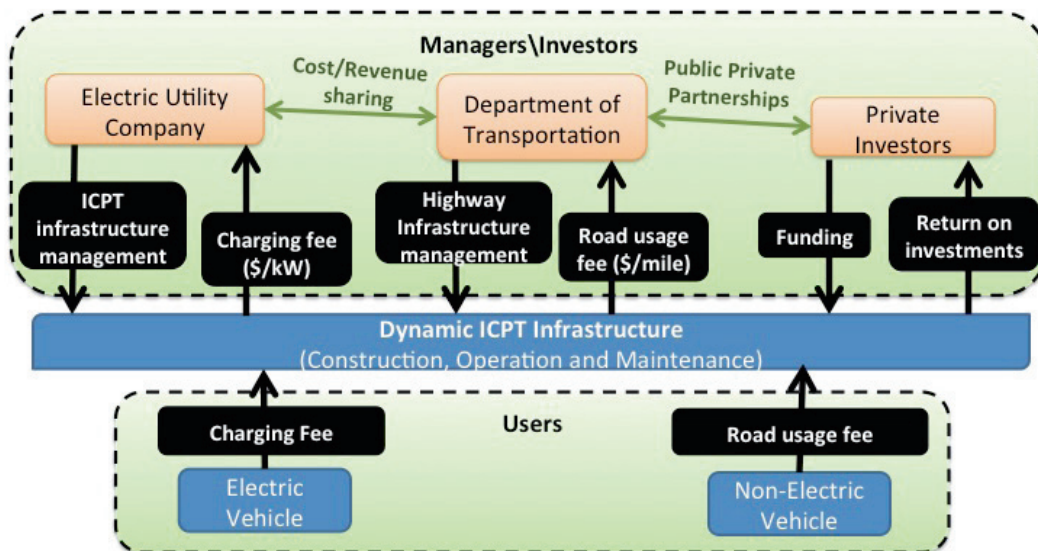


Fig. 2. Conceptual Flow Chart of the Business Model

vehicle-miles travelled (VMT) and could be tracked with current technologies such as Geographical Positioning System (GPS) devices³⁰. This fee could also be viewed as a penalty for not driving zero-emission vehicles. The EV drivers would pay through a charging subscription plan with the electric utility company. They would be charged for the energy received through the ICPT power strips, similar to the E-ZPass automatic, electronic toll collection system that currently allows traffic to travel through toll facilities quickly and efficiently³¹. This type of “smart grid internet for electricity” has also attracted numerous private investors, including auto makers like GM, Ford, Toyota, and Nissan, as well as several information technology companies like IBM, Google, Cisco, and Microsoft³². The utilities would then give a predetermined share of this revenue from the subscription plans to the DOT to help maintain the ICPT infrastructure. In addition, congestion pricing and toll roads for all users in the highway system can provide a demand management approach to traffic congestion while also generating extra revenue to support highway infrastructure like the ICPT systems.

Other government policies that are being taken to promote and reward the savings that EV technologies generate include: monetary bonuses for reducing carbon dioxide emissions, government sponsored warranties for batteries and CS infrastructure, and numerous tax credits for both EV and EV infrastructure construction³³. As the number of EV users in the system increases, the ICPT infrastructure will be better funded and thus better supported and maintained. Cost to EV drivers will be linked mainly to the scope of the implementation of ICPT infrastructure and the number of users that will actually use the system. Effectiveness and reliability of the ICPT infrastructure plays a major role in it, as that is the technology needed to overcome the current market barriers of EV technology, such as range anxiety and EV’s limited range.

5. Conclusions

The key challenge in making ICPT infrastructure readily available for EV drivers lies in the fact that such infrastructure has large construction, maintenance, and operational costs. ICPT charging, like other EV charging schemes, has its advantages and disadvantages; however, when it is fully integrated into the transport network, it will theoretically give EVs an indefinite driving range while still minimizing battery costs. As found in this research through an analysis of available information, ICPT infrastructure will foster EV market penetration by providing fast, reliable charging of the EV battery; however, in order to create such a network, much collaboration between stakeholders will be needed in order to fund the initial infrastructure. It is vital that all stakeholders collaborate together and combine their expertise and resources in order to maximize the benefits of the ICPT system for facilitating EV charging operations.

The unique business aspect of the envisioned business model allows for the DOT to utilize services and revenue from other stakeholders such as utility companies, EV and non-EV drivers, and other interested private companies while still maintaining control over the construction and direction of what could be a very powerful and influential system for the market penetration of EVs. By sharing the costs with other stakeholders, this business model could produce a way to finance the development of ICPT infrastructure, and once developed, the system could remain self-supporting once the EV market penetration level becomes large enough. For this business model, it would be most economically feasible to implement ICPT infrastructure in targeted large cities where EV densities are the highest. From there, the infrastructure could expand outward to arterials and into smaller cities as the market penetration level of EVs continues to increase.

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